

GRAIN BOUNDARY OXIDATION AND LOW-CYCLE FATIGUE  
AT ELEVATED TEMPERATURES\*

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ABSTRACT

Fatigue life consists of fatigue crack nucleation and propagation periods. In order to predict fatigue life accurately, a methodology for the quantitative assessment of these two fatigue damage processes had to be devised.

Grain boundary oxidation penetrates faster than does oxidation within a grain. This faster oxidation penetration causes intergranular fatigue failures at elevated temperatures. Grain boundary oxidation accelerates both crack nucleation and propagation.

Grain boundary oxidation kinetics and the statistical distribution of grain boundary oxide penetration depth were measured. Quantitative applications of the grain boundary oxidation kinetics to fatigue crack nucleation and propagation were analyzed. A method, based on the Weibull distribution, of extrapolating the laboratory oxidation data measured with small samples to large engineering structures is presented.

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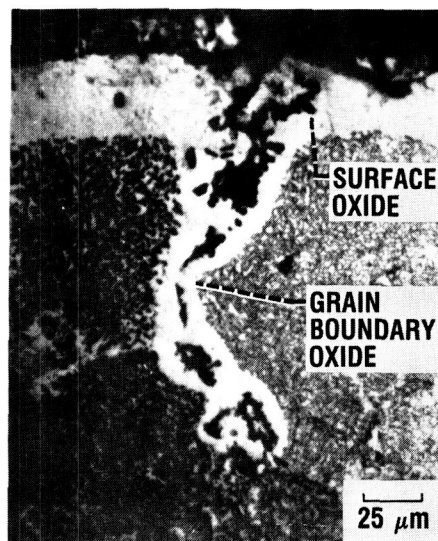
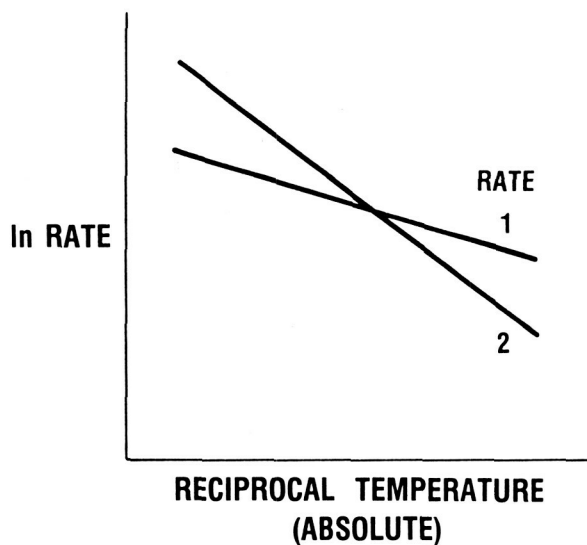
\* Work performed for Fatigue and Fracture Branch and funded under NASA Grant NAG3-348 (monitor: Jack Telesman).

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## OVERVIEW

### DAMAGE MECHANISMS OF HIGH-TEMPERATURE, LOW-CYCLE FATIGUE

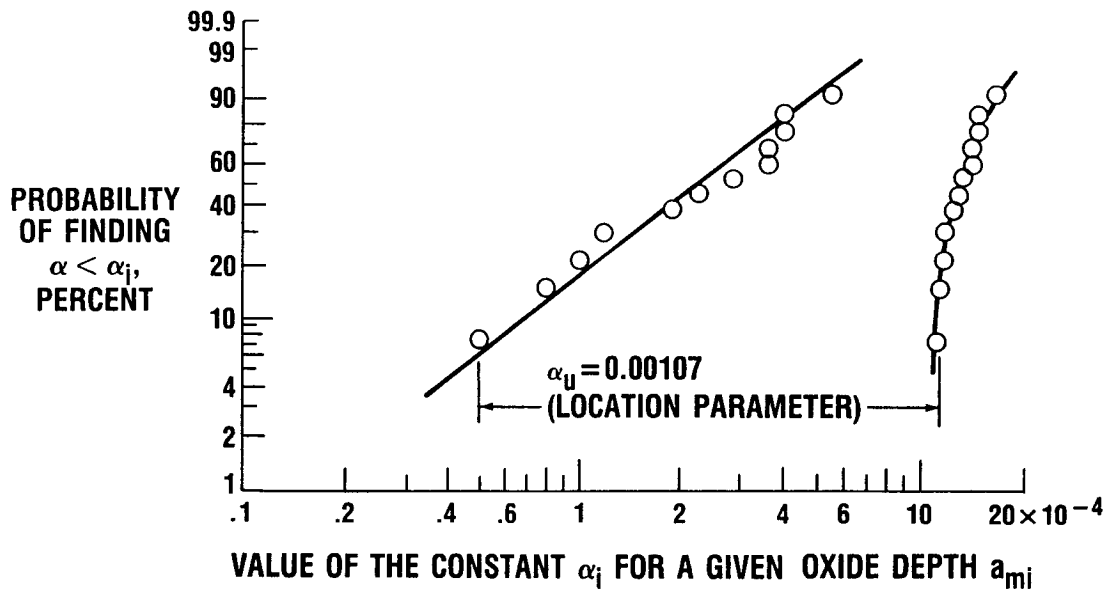
At high temperature both creep and oxidation are distinctive LCF damage mechanisms. Need exists to identify the regions at which each mechanism is dominant. A quantitative study of grain boundary oxidation and its effects on fatigue life was conducted.



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# STATISTICAL DISTRIBUTION OF GRAIN BOUNDARY OXIDE PENETRATION

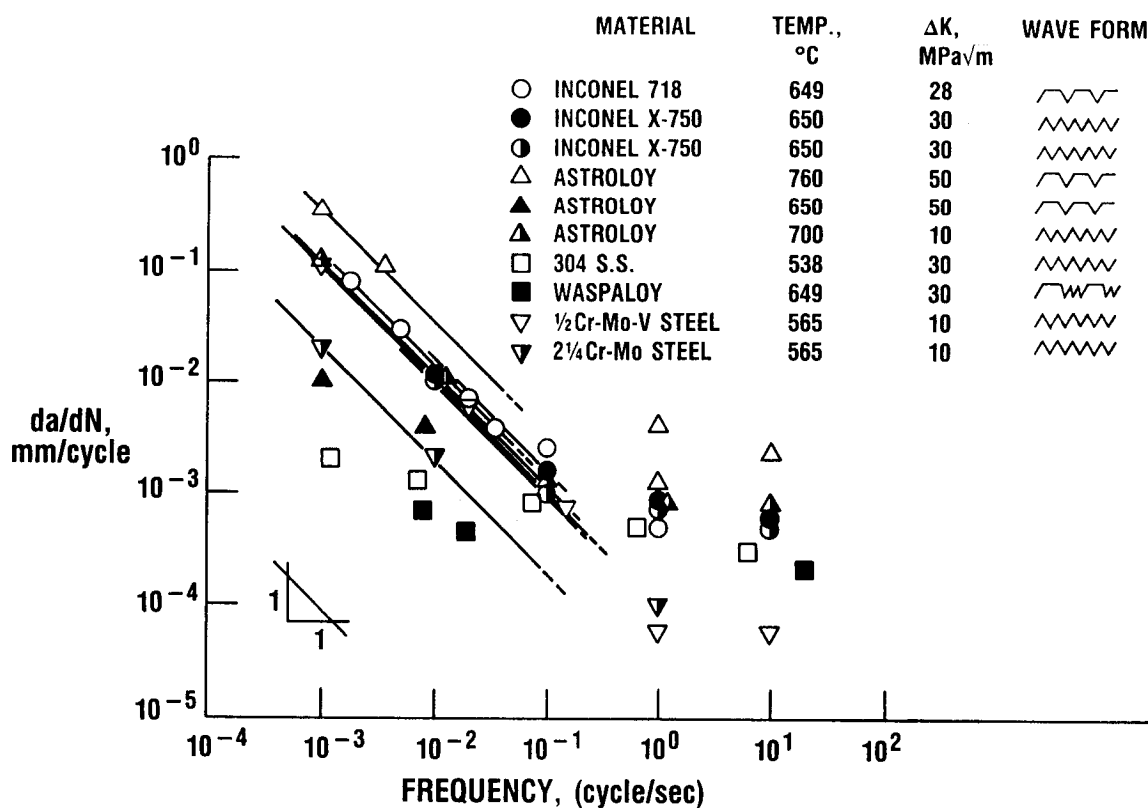
Grain boundary oxide penetration depth was measured as a function of oxidation temperature  $T$  and exposure time  $t$ . The penetration depth exhibited a wide statistical scatter which followed the Weibull distribution function as shown below. The distribution function allowed the extrapolation of the small laboratory samples to the large engineering components in service.



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# FREQUENCY EFFECTS ON FATIGUE CRACK GROWTH AT HIGH TEMPERATURE

A model is proposed that predicts fatigue crack propagation behavior of high temperatures. The model is based on an intermittent microrupture of oxide particles which is controlled by grain boundary oxidation kinetics. The model predicts an inverse relationship between  $da/dN$  and cyclic frequency. This relationship agrees with observed behavior of a number of materials.



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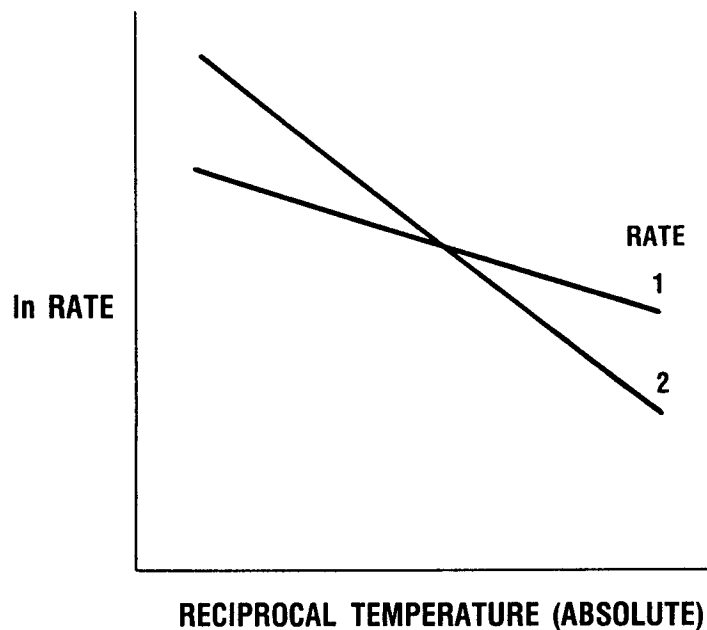
## POSTER PRESENTATION

### DAMAGE MECHANISMS OF HIGH-TEMPERATURE, LOW-CYCLE FATIGUE

Two primary damage mechanisms of high-temperature, low-cycle fatigue are creep and oxidation. Both mechanisms are thermally activated as illustrated schematically below.

The question is not which of these two mechanisms is dominant. The pertinent question is rather which one is dominant in the high-temperature region and which in the low-temperature region. Quantitative studies on creep and oxidation damage mechanisms are necessary in order to answer this question.

A quantitative study on grain boundary oxidation and its effects on fatigue life was conducted.



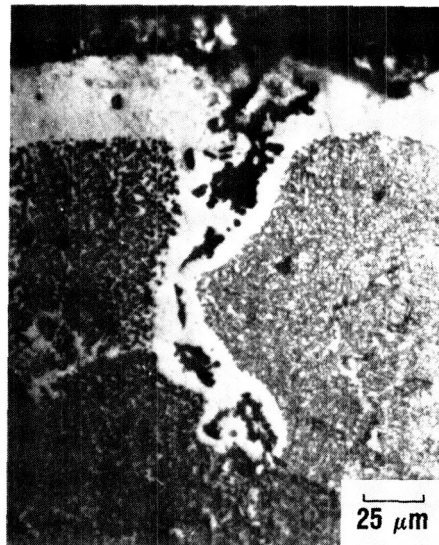
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#### OXIDATION AT GRAIN BOUNDARIES

A grain boundary is a path for rapid diffusion. Grain boundary oxidation is controlled by the diffusion of oxygen along the boundary. The rapid oxygen diffusion causes a deep grain boundary oxidation penetration, and the fast oxidation penetration causes the accelerated intergranular fatigue fractures at high temperatures.

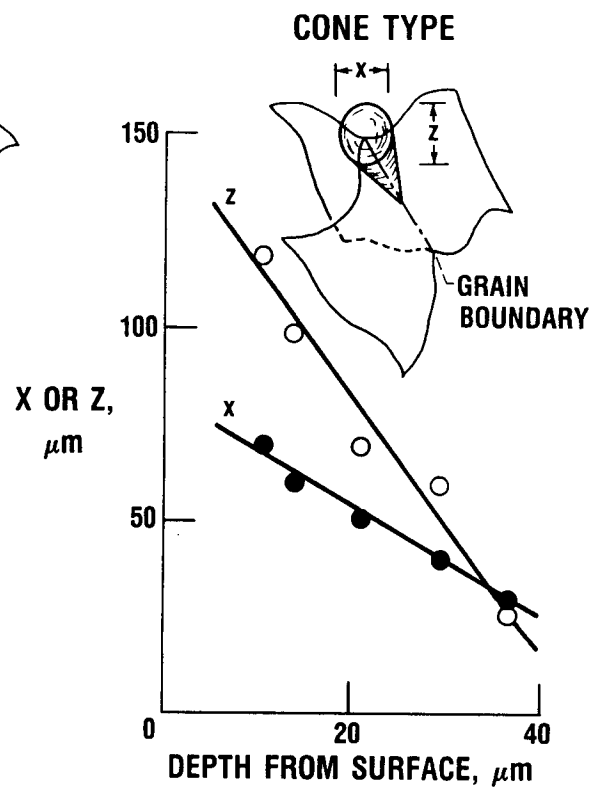
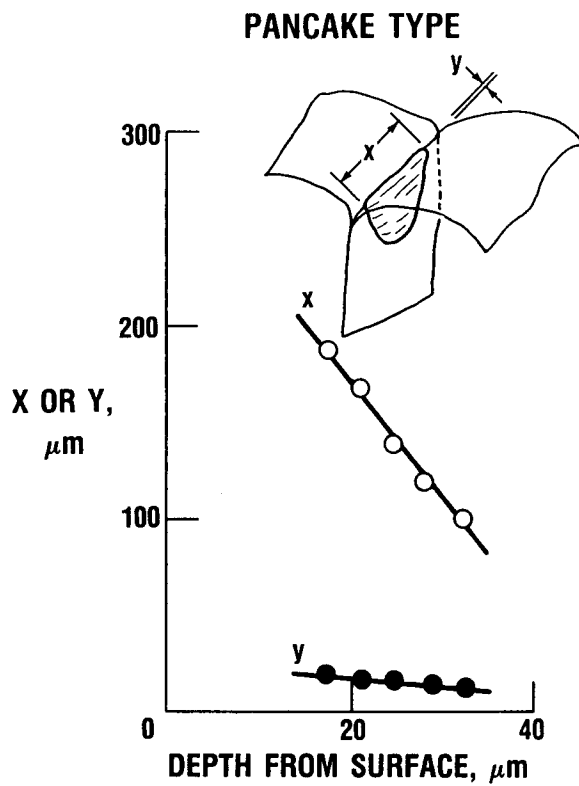
#### TAZ-8A AT 1000 °C FOR 500 HOURS



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## GRAIN BOUNDARY OXIDE MORPHOLOGIES

Two different grain boundary oxide morphologies were found: the pancake type and the cone type. The larger and deeper pancake type is more damaging.



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## RELATIONSHIPS MEASURING OXIDE PENETRATION OF GRAIN BOUNDARY

Grain boundary oxide penetration  $a_m$  in the cobalt-base superalloy, TAZ-8A, was measured by Liu and Oshida (1984 and 1985) and Oshida and Liu (1985 and 1988) as a function of oxidation temperature  $T$  and exposure time  $t$ .

The coefficient of correlation is 0.96 for 144 data points. This quantitative relation was used to study the accelerated fatigue crack nucleation and fatigue crack growth rate at elevated temperatures.

$$\begin{aligned} A_m &= \alpha t^n \exp\left(\frac{-Q}{RT}\right) \\ &= 1.34 t^{0.25} \exp\left(\frac{-4.25}{RT}\right) \end{aligned}$$

**WHERE**

**Q = APPARENT ACTIVATION ENERGY**

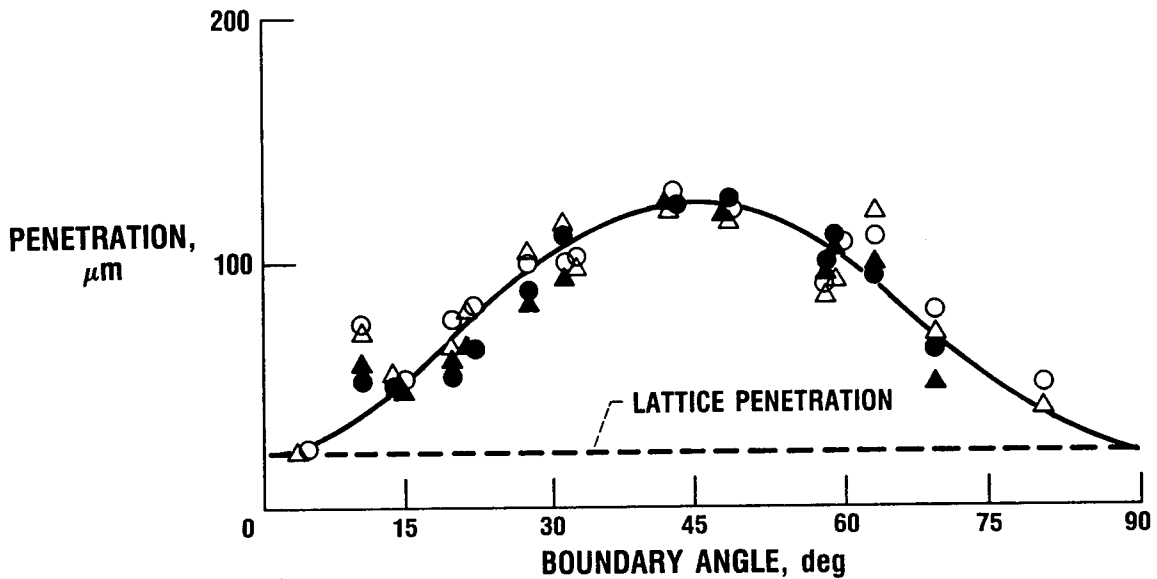
**R = GAS CONSTANT**

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## RADIOACTIVE NICKEL PENETRATION AT GRAIN BOUNDARY

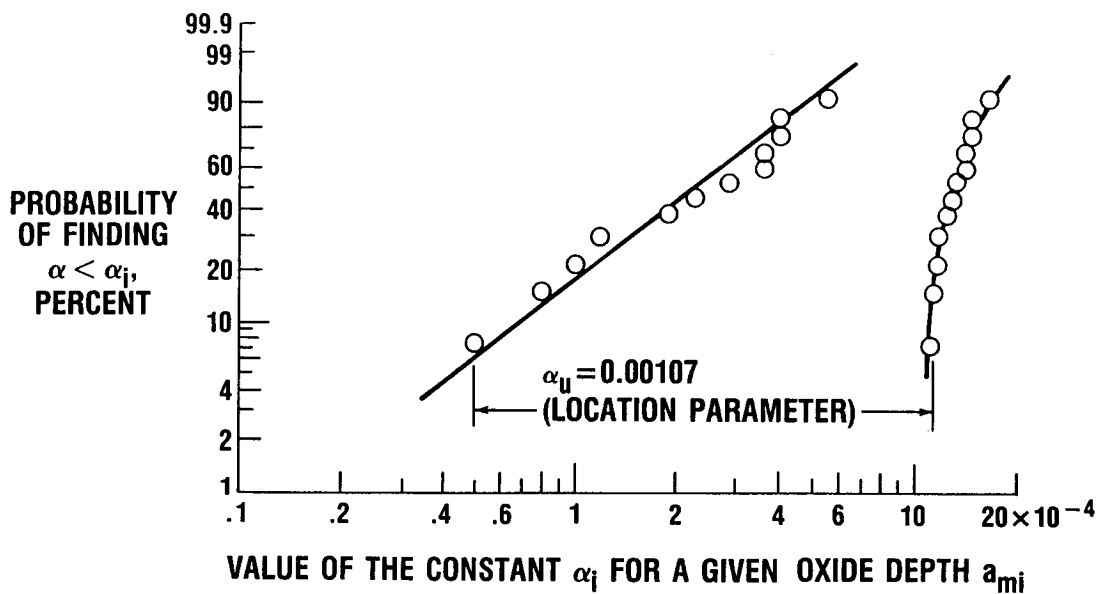
Grain boundary morphology and the chemical elements in a grain boundary may also cause the wide variation in the grain boundary oxide penetration. This wide variation may cause wide variations in the rates of crack nucleation and growth and fatigue life. Grain boundary penetration by impurities (radioactive nickel) is a function of the orientations of neighboring grains as shown below.



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# STATISTICAL DISTRIBUTION OF GRAIN BOUNDARY OXIDE PENETRATION

The statistical scatter of the grain boundary oxide penetration depth follows Weibull's distribution law as shown below. The variation of the calculated values reflects the statistical scatter of the measured oxide values. The empirical distribution law can be used to extrapolate the data obtained in a laboratory by using small samples to a much larger structural component in service.



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## EFFECT OF PRECRACK ON LOW-CYCLE FATIGUE

When an oxide reaches a critical size under given loading conditions, it will fracture. A grain boundary oxide crack becomes a fatigue crack nucleus, or a precrack. The precrack will shorten the crack nucleation period and the total fatigue life. This reduction in nucleation life will be significant if the cyclic frequency is very low, the temperature is very high, and the oxidation exposure time is very long.

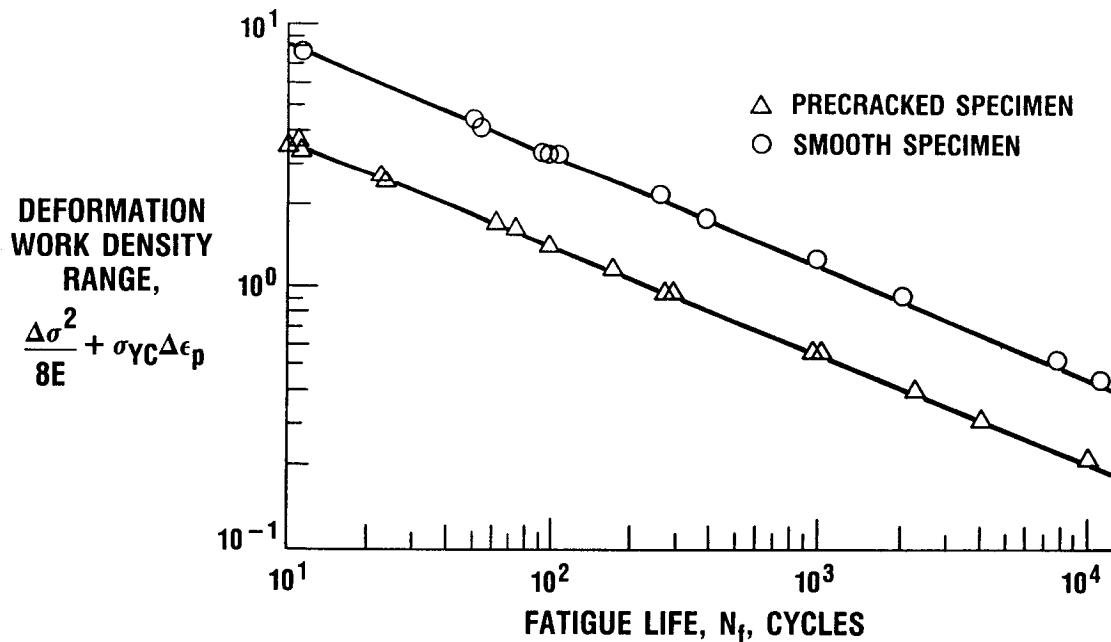
The ratio between the fatigue life of a precracked specimen and the fatigue life of a smooth specimen is a function of the precrack size:

$$N_{fi}/N_{fo} = f(\text{precrack size})$$

where  $N_{fi}$  is the fatigue life of a precracked specimen and  $N_{fo}$  is the fatigue life of a smooth specimen. The functional relationship between the ratio and the precrack size can be found empirically.

The wide variations in oxidation penetration and oxide crack size may cause a wide variation in  $N_{fi}$  and the total fatigue life. A large structural component has a high probability of having a large oxide crack and a short fatigue life. The empirical relation of the equation, together with the grain boundary oxide penetration kinetics and the Weibull distribution, would be able to predict the effect of the oxide crack on the nucleation life of a structural component.

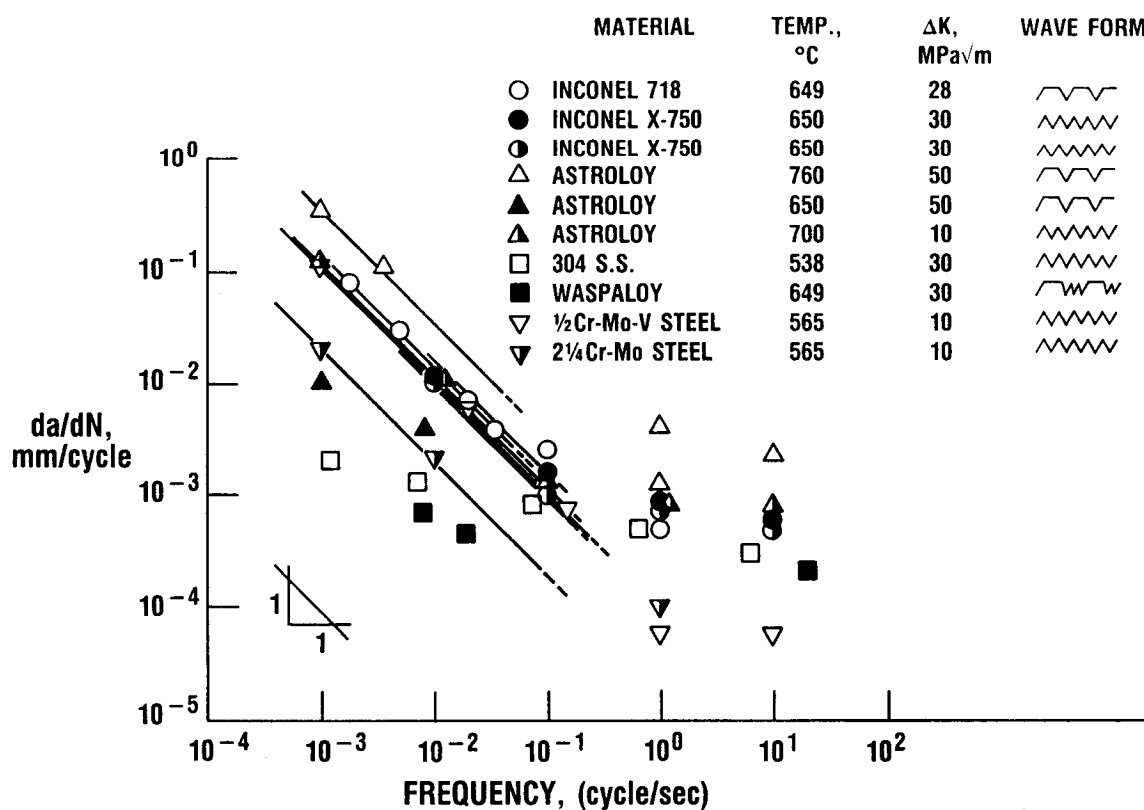
In conclusion, quantitative studies based on the physical damage mechanisms will lead to an improved life-prediction methodology.



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# FREQUENCY EFFECTS ON FATIGUE CRACK GROWTH RATE AT HIGH TEMPERATURE

The basic concept of grain boundary oxidation kinetics was used to analyze fatigue crack growth rate at the elevated temperatures. A high-temperature fatigue crack growth model based on intermittent microruptures of grain boundary oxides was proposed. The model is consistent with the observed intergranular fracture and the observed inverse relationship between crack growth rate and the cyclic frequency in the low-frequency region as shown in the figure (Oshida and Liu, 1984 and 1985), Liu and Oshida (1985 and 1986). In the high-frequency region fatigue failure could be mixed intergranular and transgranular or transgranular entirely.



## REFERENCES

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